Fuzzy Supervisory Assisted Impedance Control to Reduce Collision Impact

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Abstract - Under any abnormal loading on the manipulator end-effector, instability in motion and secondary damages are to be expected. We study a novel approach for active control of the robot manipulator trajectory within and after the impulsive loading caused by collision. Here we have adopted the position-based impedance controller as a force control strategy, inspiring human reaction against the sudden and impulsive loadings. The approach is to issue a new position command along the impact direction and routing smoothed trajectory just after the impact loading. Due to variant properties of impact and to translate human reactions amid impact interval, fuzzy logic-based supervisory system is utilized to modify impedance parameters. Fuzzy rule-based and inference system are defined and resulted control surfaces are illustrated. Finally the response of the system is compared with the case without the proposed controller in the overall scheme. The result shows significant increase in stability and decrease in torque dissipation and therefore, a reasonable reduction in collision impact.

Keywords—Collision Impact; Impulsive loading; Instability in motion; Impedance Control; Fuzzy supervisory.

I. INTRODUCTION

In the manipulation tasks, often there is a mechanical interaction between robot arm and objects to be manipulated. For example: welding operation, threading and simple displacement of work. During such operations, there may occur unwanted collisions between the robot end-effector and environmental objects that cause excessive pressure on the actuator and also it may lead to instabilities in the arm motion that strongly influences the performance of manufacturing job. In recent years, many research studies have focused on the development of impact control. Especially, an impact video of a hand-arm robot developed by the researchers in German Aerospace Center (DLR) to endure a smash added by a young man using a baseball bat was well received in robotics engineering. The solution, the DLR group figured, was to completely rethink the design of robotic joints and actuators. For the upper arm, the researchers designed intricate shock-absorbing structures that they called "floating spring joints". Another study [1] presents a novel control method to reduce impulse force during collision between a mobile manipulator and its surrounding environment by optimizing inertia property of the manipulator and employing damping-based motion control.

In this study, we will present a novel approach to control the robot motion within and after the collision, taking into account the force feedback of the impact exerted by external object on the arm of the manipulator. In other words, the approach is to adjust the relation between position and force to achieve desired behavior. Literature review shows that impedance control can be a useful candidate. Impedance control was first proposed by Hogan [2]. This principle is to monitor end-effector behavior such that the system remains stable when it contacts with the environment or external objects. In the ground view of contact task control, Morel and Bidaud [3] proposed an adaptive impedance control in order to deal with dynamic perturbation, environment behavior changes, uncertainties and impact to track the desired force in task space. In other investigation, Lin et al. attempted to control the robot arm impedance to minimize impact of collision with the environment [4]. They have succeeded to reduce the impact effect by assuming a virtual mass for the arm and reducing that virtual mass. Moosavian et al. simulated a system of manipulators mounted on a space free-flying robot moving an object based on given trajectories, which come across an obstacle. Multiple Impedance Control (MIC) was used as the positioning algorithm. It was shown that the contact force retained to the desired force trajectory besides satisfying the grasp constraint [5, 6].

In the present work, based on the characteristics of impedance control, the controller is designed and the behavior of single joint robot arm driven by DC motor is analyzed against the impulsive loading due to collision of the external object. As depicted, the problem mainly arises from the lack of any monitoring on the developed torque that leads to overloading during collision and also unstable motions and switching of developed torque by actuator, just after loading vanishes. The aim of the present work is to consider specific impedance for the robot arm and enhance its flexibility. This theory originates from the fact that when a fist hits your body, in order to reduce collision effects, you won't resist against it, instead, you want to "pull back" your body and show some flexibility.

In some previous researches, artificial intelligent (AI) algorithms have been utilized in order to adapt impedance control with the situation [3, 7, 8, 9, 10, 11, 12]. In our case also, due to variant properties of impact and to translate human reactions amid impact interval, fuzzy logic-based supervisory system is utilized to schedule impedance parameters based on predefined features. Usefulness of fuzzy logic-based algorithms have been ensured by many researchers [3, 7, 11, 12]. For example, Ren presented an impedance control method for high...

II. IMPEDANCE CONTROL

The control objective of an impedance controller is to impose, along each direction of the task space, a desired dynamic relation between the manipulator end-effector position and the force of interaction with the environment [2, 3, 4, 13]. In other words impedance, which is ratio between force and position [12], leads the robot arm behaves as a mass-spring-damper system. There is two approaches regard to the impedance implementation type, position-based and torque-based. In this work has adopted the position based method because of more stability in performance [13]. However strategy of the position-based impedance control is position control approach but with some considerations has great ability to regulate contact interaction force. Positions are commanded and impedances to achieve better force response are adjusted [14]. Contrast to single position controller, impedance control is able to correct position command according to the interaction force of manipulator end-effector and external factor [15].

When the impact exerted on the end-effector, overloading may occur in the absence of any monitoring on the torque, but here the impedance controller as a torque monitoring unit generates small movement in direction of impact that causes reduction in the motor generated torque. In fact, during this procedure accuracy decreases but the time for impact damping increases. So there is further time to import required energy to procedure accuracy decreases but the time for impact damping reduction in the motor generated torque. In fact, during this generates small movement in direction of impact that causes here the impedance controller as a torque monitoring unit may occur in the absence of any monitoring on the torque, but also reference such controllers which lead to force control requires expecting optimization of the motor generated torque. Implementation of system for damping of impulsive loading, which results in increases. So there is further time to import required energy to system for damping of impulsive loading, which results in optimization of the motor generated torque. Implementation of such controllers which lead to force control requires expecting feedback of position and interaction force, and also reference and modified trajectory integration [15].

III. MODELLING

The general dynamic equation of n degree of joints freedom robot manipulator [4] is given by:

\[ M(q) \ddot{q} + h(q, \dot{q}) + g(q) = \tau + J(q)F_e \]  (1)

where:

- \( q, \dot{q}, \ddot{q} \) are angular position, velocity and acceleration of joints, [rad, rad/s, rad/s^2];
- \( M(q) \) is the \( n \times n \) symmetric positive definite inertia matrix, [kg.m.rad/rad];
- \( h(q, \dot{q}) \) is torques arising from coriolis centrifugal and frictional forces, [N.m];
- \( g(q) \) and \( \tau \) represent gravitational and joints torque, respectively, [N.m];
- \( J(q) \) is the Jacobian matrix, [m];
- \( F_e \) is the force vector of external factor, exerted on the robot arm,[N].

For given arm in Fig. 1 we have all inertia connected to the joint as inertia term and all frictions connected to the joint as frictional term, while there is no gravitational term. So the dynamic equation of the robot arm is given as:

\[ \tau_m = J\dot{\theta}_m + D\dot{\theta}_m + \tau_{mt} \]  (2)

where:

- \( \tau_m \) is the motor developed torque, [N.m];
- \( J \) is all inertia connected to the joint as inertia term and all frictions connected to the joint as frictional term, [N.m.s^2];
- \( D \) is all friction connected to the joint as frictional term, [N.m.s];
- \( \tau_{mt} \) is all torques connected to the arm which is reflected by gears to the motor shaft, [N.m];
- \( \dot{\theta}_m \) and \( \dot{\theta}_m \) are the motor shaft angular position and velocity respectively, [rad/s, rad/s^2].

In the present case all friction connected to the motor shaft includes the motor friction only and all inertia connected to the motor shaft is result of the rotor inertia and the arm inertia.

\[ J = J_{ml} + J_m \]  (3)

where,

- \( J_{ml} \), is the reflected moment of inertia of arm to the drive[N.m.s^2];
- \( J_m \), is the rotor moment of inertia[N.m.s^2].

The arm moment of inertia and torque which are reflected by gears into drive are as following:

\[ J_{ml} = \frac{J_L}{n^2} \]  (4)

\[ \tau_{ml} = \frac{\tau_L}{n} \]  (5)

where,

- \( n \) is gear ratio,[\( \ast \)];
- \( J_L \) and \( \tau_L \), are moment of inertia and load on arm, respectively, [N.m.s^2, N.m].

Equations (4) and (5) mean that the gear ratio reflects diminished moment of the inertia and the torque of the arm into drive. The arm angular position, \( \dot{\theta}_m \), differs from the motor shaft angular position, \( \dot{\theta}_m \), and their relation is defined in (6).

\[ \dot{\theta} = \frac{\dot{\theta}_m}{n} \]  (6)

In this study the force element is a linearly elastic spring, in a way that it opens in specific time (commencement of impact) and hits the robot arm[16]. Exerted force \( f_e \) on the arm by some considerations can be simplified by (7).

\[ f_e = k((\theta - \theta_t)l + x_e), (\ddot{d}, \ddot{n}) \]  (7)
where,

- $x_c$ is the initial compression of virtual spring,[m];
- $\theta_r$, is the joint reference angular position,[rad];
- $k$, is the stiffness of virtual spring,[N/m];
- $l$, is the arm length,[m];
- $\vec{n}$, is the normal vector to the arm and $\vec{d}$, is the vector presenting direction of spring.

IV. IMPLEMENTATION OF IMPEDANCE CONTROLLER

Usually, the desired impedance is chosen linear and of second order, as in a mass-spring-damper system [17]. Higher order impedances have a less well-known behavior and require additional state variables. In order to fulfill the task requirements, one can choose a desired end-effector impedance that may be expressed by (8).

$$M_d(\dot{\epsilon}) + B_d(\dot{\epsilon}) + K_d(\epsilon) = F_e$$

where,

- $e = X - X_r$ is the difference between position vector ($X$) and reference position vector ($X_r$) of manipulator links,[m];
- $\dot{\epsilon}$ and $\ddot{\epsilon}$ are corresponding velocity and acceleration,[m/s, m/s²];
- $M_d, B_d$ and $K_d$ are symmetric positive definite matrices that represent the desired inertia, damping and stiffness of the end-effector,[kg,N·s/m, N/m];

Parameters above are general and for the arm which has shown in Fig. 1, are concluded as following:

$$m_d(\Delta \theta) + b_d(\Delta \theta) + k_d(\Delta \theta) = f_e, \Delta \theta = (\theta - \theta_r)$$

where,

- $\theta, \dot{\theta}$ and $\ddot{\theta}$ are the joint angular position, velocity and acceleration, [rad, rad/s, rad/s²];
- $\theta_e, \dot{\theta}_e$ and $\ddot{\theta}_e$ are the joint reference angular position, velocity and acceleration, respectively, obtained by the cinematic relations, [rad, rad/s, rad/s²];
- $m_d, b_d$ and $k_d$ represent the desired inertia, damping and stiffness of the arm and are scalars [kg·m/ rad, N·s/ rad, N/ rad];
- $\theta$ is a generalized value of the position and the impedance controller generates modified position ($\Delta \theta$) according to (10).

$$\frac{\Delta \theta}{f_e} = \frac{1}{m_d \dot{\theta}^2 + b_d \dot{\theta} + k_d}$$

From (10) it is concluded that the impedance controller is stable as long as parameters $m_d$, $b_d$ and $k_d$ are chosen strictly positive. However, because of unmodeled destabilizing effects (dry friction, backlashes, actuator saturations,...), the gains are practice limited by maximum values [3]. The intrinsic inertia of arm is due to its mass[17], so here the problem of the choice of the desired impedance is reduced to the choice of $b_d$ and $k_d$. The more damping coefficient ensures the more stability of controller [3, 7, 19] where the more stiffness implies the more resistance of robot arm against the impact.

V. IMPLEMENTATION OF FUZZY SUPERVISORY

Due to variant properties of the impacts, various adjustments of the impedance controller parameters are required. Also as:

1. The proposed strategy of control is inspired from human reaction against suddenly impacts,
2. Fuzzy logic is a way to give mathematical rules eliciting them from human linguistic recognition,
3. so to regulate the impedance controller parameters, a fuzzy logic based supervisory system has been utilized. This system adjusts the controller parameters based on the predefined features.

A. Fuzzy Supervisory

The fuzzy supervisory control technique utilizes a hierarchical structure consists of sub-controller at a lower level and a fuzzy adaptor at a higher level [7], as shown in Fig. 3. The basic advantage of this two-level control is that different controllers can be designed to target different purposes, so that every controller is simpler and performance is improved [18]. The basic idea of supervisory process control based on fuzzy logic is to formulate sets of rules for automatic operation based on human linguistic recognition [20, 21].
Fig. 3 Architecture of a two-level fuzzy control system, where the lower-level sub-controller is under supervision of higher-level fuzzy system.

The terms high, near, away and medium are represented by membership functions (MF), and fuzzy inference calculates the resultant of the rules. The condition of a rule is fulfilled to a certain degree of membership, and each rule affects the result of the set of the rules in coordination with its grade of fulfilment. The accumulation is a trade-off between all conclusions where each conclusion has a specific weight [9, 20].

B. Implementation

The proposed controller design is shown in Fig. 4. Inputs for fuzzy supervisory system are three: Contact force \( f_c \) and force increment in respect to joint position increment \( \Delta f_c/\Delta \theta \), as impact features and deviation from motor nominal torque \( (\tau_m - \tau_N) \) as a feature that describes pressure on the motor. Outputs of the fuzzy controller are the stiffness and the damping coefficient, which provide for the direct adaptation of the impedance controller. The adopted fuzzy inference engine is "Mamdani". (See TABLE 1)

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**TABLE 1**

<table>
<thead>
<tr>
<th>Properties of Fuzzy Inference System</th>
<th>Value</th>
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<tbody>
<tr>
<td>Inference engine</td>
<td>Mamdani</td>
</tr>
<tr>
<td>Fuzzification</td>
<td>Singleton</td>
</tr>
<tr>
<td>AND method</td>
<td>product</td>
</tr>
<tr>
<td>OR method</td>
<td>algebraic sum</td>
</tr>
<tr>
<td>Implication</td>
<td>product</td>
</tr>
<tr>
<td>Aggregation</td>
<td>summation</td>
</tr>
<tr>
<td>Defuzzification</td>
<td>centroid of area</td>
</tr>
</tbody>
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Fuzzy partitioning of the inputs after normalization has been performed by choosing 3 and 2 primary fuzzy sets for the selected impact features and \( (\tau_m - \tau_N) \) respectively, indicated with linguistic labels that appear in the fuzzy rules (see Fig. 5). The membership functions corresponding to the outputs have been chosen in 5 grade [Very Small, Small, Medium, Big and Very Big]. Note that the crisp output is taken into account after denormalization between predefined upper and lower limit of stiffness and damping. The applied rule base consists of all 18 rules, which are shown in TABLES 2-5. For instance the upper left corner rule of the rule base presented in TABLE 4 is:

\[
\text{IF } (\tau_m - \tau_N) \text{ is Negative and contact force } (or \ f_c) \text{ is Small and } \Delta f_c/\Delta \theta \text{ is Small THEN } b_d \text{ is Very Big}
\]
The rules in Tables 2, 3, and 4 produce decisions about the stiffness and the damping, respectively. Critical moment is especially when the contact force reduces to zero, meaning that the arm suddenly desists from "pull back" and starts to "push forward". This problem is obviated by choosing the greater damping coefficient (see the latter mentioned rule in Table 4.)

Control surfaces of the fuzzy controller are shown in Figures 6 and 7. Note that all the inputs and outputs have been normalized. It is clear that the output of the both stiffness and damping parameters is very big when the both impact features are reaching low positive values and vice versa. It means that the greater collision impact implies the more flexibility of the arm to "pull back" and the smaller collision impact implies the more resistance against impact. In other regions of the control surfaces normal adaptation of the parameters of the impedance controller is performed which is adequate to lead the system to the desired state. The impedance controller is stable as long as the applied bounds of output denormalization are strictly positive.

![Fig. 6 Control surface of the fuzzy controller for stiffness while \( (\tau_m - \tau_e) \) is zero.](image)

![Fig. 7 Control surface of the fuzzy controller for damping while \( (\tau_m - \tau_e) \) is zero.](image)

| TABLE 5
Fuzzy rules for damping adaptation, IF \( (\tau_m - \tau_e) \) is positive |
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>( f_e ) ( \Delta f_e )</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>Small</td>
</tr>
<tr>
<td>Small</td>
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VI. SIMULATION AND RESULTS

In order to perform the simulation, Simulink environment of matlab software has been used. Maxon dc motor model EC 45 flat 339285 was selected with 10 gearbox ratio. \( R, L, K_e, K_f \) stand for the motor resistance, inductance, back electromotive constant and armature constant, respectively. These parameters and the values of \( J, D \) and \( \tau_N \) have gathered in Table 6.

![Table 6](image)

It assumed that the direction of impact is parallel by the freedom of the arm and before the collision, the arm is stationary in \( \theta_e = 30° \) and also supposed that the force sensor has been set in the target of the collision. The impacts occurs in the time interval \([5, 5.3]\). According to Fig. 8 just after the external factor hits the target, the impedance controller generates a new trajectory for the inner loop and it introduces the immediate 'pull back' from the reference point. The case has sensible reduction in the torque dissipation in comparison to the absence of the proposed controller (i.e. single PID position controller). At the commencement of the impact because of the high impact intensity the fuzzy supervisory regulates the impedance controller with the smaller stiffness and damping parameters which prompts rapid 'pull back' from the reference point and prevents overloading. The moving back continues until the contact between the arm and external object vanishes. From then on the fuzzy supervisory by commanding more damping hinder sudden "push forward" movement and leads to smoothed return to the reference point. Whereas according to the obtained result in the absence of the impedance controller with the fuzzy supervisory, just after the loading has been vanished, there are sudden move back and torque switching.

VII. CONCLUSION

In this work, the impedance control was proposed in order to reduce collision impact exerted on the robot arm. Under impulsive loadings, overloading may occur in the absence of any monitoring on the torque. Also due to sudden unloading, instabilities in the end-effector trajectory and torque switching are to be expected. For monitoring the torque, the impedance control was implemented by assisting the fuzzy supervisory system, inspiring human reaction against impacts. The supervisory system was used to regulate the impedance control parameters (stiffness-damping) and just after collision. Therefore the rule-based was defined and control surfaces were discussed. Immediate "pull back" was attained commanding small amounts of damping and stiffness by fuzzy supervisory system in the commencement of impact exertion. This move back resulted in the reduction of torque dissipation and diminishing probability of overloading, too. Also after loading vanished, fuzzy supervisory in higher level by commanding the
big amounts of damping prevented from suddenly "push forward" movement and led to the smoothed behavior returning to the reference point. So it was concluded that the proposed controller was applicable to diminish collision impact.

**Fig. 8. Simulation result.** (a) joint angular position (b) motor torque, impact characteristics: $k = 100 \text{ N/m}$, $x_c = 0.02 \text{m}$, duration=0.3second

**REFERENCES**


